Comparison of Total Dose Responses on High Resolution Analog-to-Digital Converter Technologies*

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Abstract

Two different 12-bit analog-to-digital converter technologies, CMOS and BiCMOS, from Burr-Brown were compared for total dose responses. The BiCMOS converter appears to be a better candidate for space applications. CMOS devices showed larger degradation with both high dose rate (HDR) and low dose rate (LDR). An external voltage reference can be used for a radiation hardened process 12-bit converter from Analog Devices to maintain accuracy up to 1 Mrad(Si). DATEL's 16-bit *hybrid* converter showed a low failure level with HDR.

I. Introduction

High-speed and high-resolution analog-to-digital converters (ADC) are critical devices for space systems. Analog Devices's bipolar technology 12-bit converter, AD574A, was proven to withstand up to 100 krad(Si) [1], but excessive power consumption limits its applications in many new high-speed and low-power system designs. Several other commercial 12-bit successive approximation register (SAR) A/D converters with BiCMOS technology from different manufacturers have been tested and showed various results [2]. Failure modes were also quite different for those converters at different dose rates [3].

This paper compares total dose effects on two different technologies (CMOS and BiCMOS) 12-bit converters from the same manufacturer, Burr-Brown. Low dose rate test for the BiCMOS converter was performed for enhanced low dose rate (ELDR) effects. A previously tested BiCMOS 12-bit converter, Maxim MX674A failed catastrophically at total dose levels below 5 krad(Si) at LDR because of ELDR effect; the converter functioned to about 25 krad(Si) at HDR and recovered quickly during annealing [3].

CMOS converters are particularly attractive in low-power circuit design applications. However, there were inherent limitations with analog CMOS technology even with self-calibration architecture as in the previously tested Crystal's CS5016 16-bit ADC [4]. This CMOS converter failed at a very low level with HDR and at a much higher level with LDR. Despite the improved failure level of some CMOS converters at LDR, BiCMOS converters showed that they were indeed better candidates for space applications provided they did not show enhanced low dose rate (ELDR) effect in their bipolar components [5-8].

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This paper discusses results for both CMOS and BiCMOS technology 12-bit converters from one manufacturer, Burr-Brown, comparing architectures and radiation response mechanisms. A radiation hardened BiCMOS process (RBCMOS) 12-bit converter, Analog Devices AD9871, was tested with HDR and would withstand the radiation level of 1 Mrad(Si) using a precision external reference. The DATEL's 16-bit *hybrid* converter, ADS937, observed a low failure level with HDR and results are compared with the previously tested Crystal Semiconductors CS5016 monolithic 16-bit CMOS converter.

II. Experimental Approach

ADC574A is fabricated with a CMOS and laser-trimmed bipolar technologies. This BiCMOS converter has internal scaling resistors that can be used to select analog input signal ranges of 0V to +10V. ADS574 is a CMOS converter which uses a capacitor array implemented in low-power CMOS technology. Key features of the device are low power consumption and internal sampling. The converter can be also operated from a single +5V supply. These are a drop-in replacements for AD574 models of other manufacturers for most applications.

The radiation hardened Analog Devices RBCMOS AD9871 is a monolithic 12-bit, 5 MSPS converter with an on-chip track-and-hold amplifier and voltage reference. This converter uses a multistage differential pipeline architecture with error correction logic to provide 12-bit accuracy. The internal voltage reference caused the converter to deviate accuracy significantly and it is discussed in the later section. DATEL ADS937 is a 16-bit 1 MHz sampling converter which contains a sample/hold amplifier, subranging A/D converter, internal reference, timing control logic, and self calibration error-correction circuitry. It is a *hybrid* converter whereas the CS5016 is a monolithic CMOS device. Table 1 in previous page lists the features of the devices studied for this paper.

Devices were irradiated with a room type irradiator, a Co-60 source, at a high dose rate of 50 rad(Si)/s and a low dose rate of 0.005 rad(Si)/s. Devices were statically biased during irradiation. Five different samples were irradiated for all tested devices except ADS937 16-bit converter. There were some part-to-part variations in test results. However, parametric degradation plots in this paper are mean values of five different samples. For ADS937, two samples each were irradiated at 5, 10, 15, 25, and 50 krad(Si) levels to meet the specified project requirement.

Table 1. Features of devices studied

Name	Manufacturer	Technology	Resolution	Input Voltage Range	Freq.	Power Consumption (Typical)
ADC574A	Burr Brown	BiCMOS	12-bit	10 V	40 kHz	325 mW
ADS574	Burr Brown	CMOS	12-bit	10 V	40 kHz	100 mW
AD9871*	Analog Devices	RBCMOS	12-bit	2 V	5 MHz	1.03 W
ADS937	Datel	Bipolar, CMOS, BiCMOS (Hybrid)	16-bit	10 V	1 MHz	1.1 W
CS5016	Crystal Semi.	CMOS (Monolithic)	16-bit	4.5 V	100 kHz	150 mW

* Radiation hardened BiCMOS process converter

III. Total Dose Radiation Test Results

A. ADC574A(BiCMOS)/ ADS574(CMOS) 12-bit Converters

The BiCMOS converter, ADC574A, requires supply voltage of 5V and ±15V. The +5V is specified as V_{logic} supply. The CMOS converter, ADS574 requires only Vdd of 5V and -15V for Vee (no +15V supply is required). The ADS574 CMOS converter is recommended for use in low-power consumption applications and is also pin-to-pin compatible with the ADC574A BiCMOS converter.

The +5V power supply current was measured at HDR of 50 rad(Si)/s and plotted in Figure 1. The nominal supply current of the CMOS converter was about 10.5 mA. It exceeded the maximum specification limit of 20 mA at about 15 krad(Si) and continuously increased until 35-40 krad(Si) where devices became nonfunctional. The parametric failure level of the supply current for this CMOS converter is slightly lower than the BiCMOS device. Although not shown in the plot after 40 krad(Si), the supply current of the CMOS device annealed and recovered to the initial values after 24 hours at room temperature. Note that dotted portion (in between open-square symbols) of the CMOS plot between 35-40 krad(Si) total dose levels where devices became nonfunctional. The supply current of the CMOS converter increased further to 34 mA when devices failed functionally at the final total dose level of 40 krad(Si).

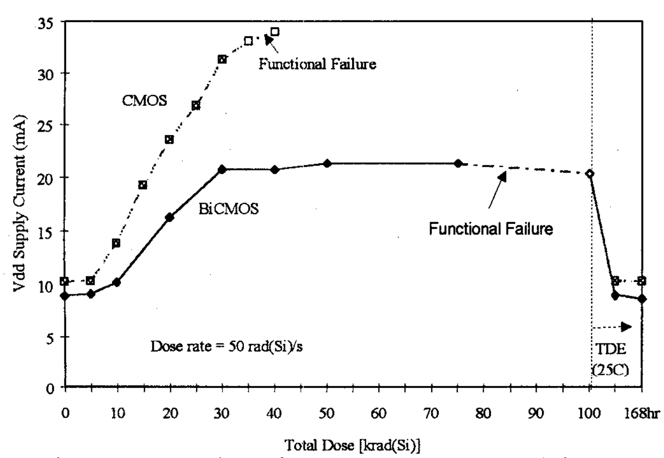

Figure 1. Comparison of V_{logic} supply current degradation at 50 rad(Si)/s.

Supply current of the BiCMOS converter sharply increased from the initial value of about 9 mA to 21 mA at 30 krad(Si) and remained at about 21 mA until the final total dose level of 100 krad(Si). It annealed back to initial values at room temperature. The maximum specification limit for supply current is 15 mA and it exceeded the specification limit at about 20 krad(Si). However, the device failed functionally at a much higher level at 75-100 krad(Si).

Conversion time of these converters is another parameter that showed significant differences in degradation with HDR as shown in Figure 2. The conversion time of the CMOS converter did not show any degradation at all up to 35 krad(Si). The converters abruptly stopped functioned at 40 krad(Si), and could not make any conversions. Thus, conversion time could not be measured at 40 krad(Si). However, the conversion time of BiCMOS converters increased gradually until 75 krad(Si), the last radiation level at which the converters were still functional. This may indicate that degradation of the bipolar device is the cause of the large increases in conversion time. Conversion time for BiCMOS devices further recovered to initial values during room temperature and high temperature (100 °C) annealing. Conversion time of both device types showed insignificant degradation with LDR up to 50 krad(Si).

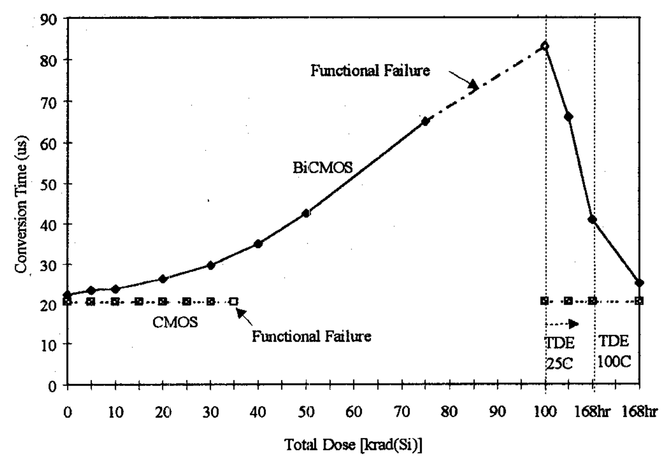

Figure 2. Conversion time degradation of two different process converters at 50 rad(Si)/s.

The last parameter that showed significant differences in radiation degradation is the integral nonlinearity (INL), shown in Figure 3. INL is the most important parameter of these SAR type 12-bit ADCs. The CMOS converter showed tremendous increase in nonlinearities from 20 krad(Si) to 35 krad(Si). When converters became nonfunctional at 40 krad(Si), INL could not be measured anymore. The INL parameter recovered during 168 hours room temperature anneal. However, it did not fully recover to the initial value. INL further recovered to the slightly larger value than initial measurements during high temperature (100 °C) annealing. It did not show full recovery after the high temperature anneal. For the BiCMOS converter, INL increased slightly and recovered during room temperature anneal. This is one of key parameters and critical results for decision making process for converter applications in space environment.

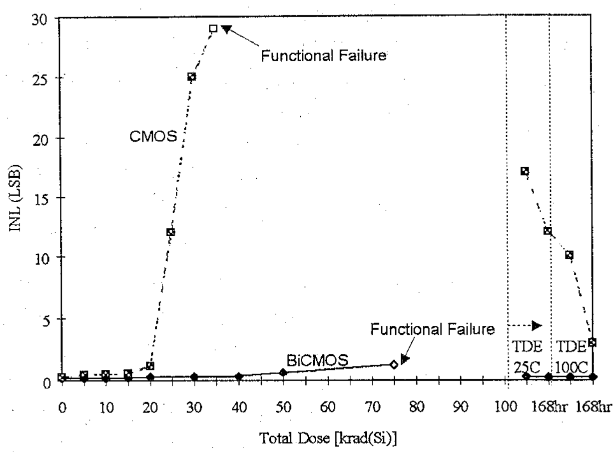

Figure 3. Comparison of integral nonlinearity degradation at 50 rad(Si)/s.

A low dose rate test of 0.005 rad(Si)/s of the converters was conducted to observe any ELDR effects on the BiCMOS device. Figure 4 shows degradation of integral nonlinearity up to 50 krad(Si) for both types of devices. No significant degradation was observed for the BiCMOS devices. However, CMOS devices showed severe degradation at 21 krad(Si). This is an unusual result because the CMOS devices showed a classical annealing after high dose rate irradiation. INL showed large changes (about 12 LSBs) at 25 krad(Si) with HDR, but it showed the same amount of degradation with LDR at slightly lower total dose level of 21 krad(Si). This may due to the sensitivity variation of COTS devices and the inherent limitation of CMOS devices response due to total dose radiation. Five samples showed some variations in the results. However, all of them showed consistent severe degradation at LDR. Note that even the BiCMOS devices showed slightly larger degradation at 0.005 rad(Si)/s than 50 rad(Si)/s. No significant degradation on conversion time was observed for both types of converters at LDR.

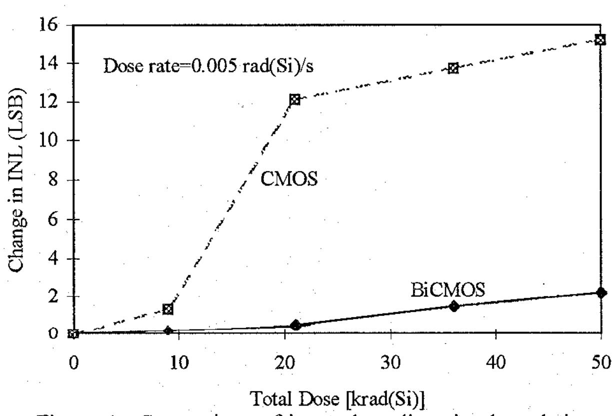

Figure 4. Comparison of integral nonlinearity degradation at 0.005 rad(Si)/s LDR.

B. AD9871 12-bit 5MSPS ADC

This radiation hardened converter has an on-board laser-trimmed bandgap reference. The output stage of the reference was designed to require the use of an external capacitor to limit the wideband noise. Therefore, a 1 μF capacitor on the reference

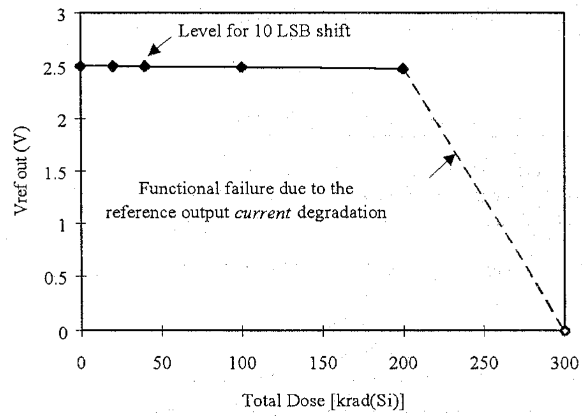

Figure 5. AD9871 reference output degradation at 50 rad(Si)/s. Functional failure occurred due to the reference output buffer current drive capability degradation.

output to the reference ground is required for stability of the reference output buffer. The reference output must be connected to the reference input to provide 2.5 V for conversion.

The internal reference output voltage degraded severely to 200 krad(Si). The reference output degraded to 0.002 V due to the output buffer current drive capability degradation. Devices failed functionally in between 200-300 krad(Si) as shown in Figure 5.

Because the internal reference failed after 200 krad(Si) irradiation, test fixtures were modified to use an external reference to see whether devices would still function or not. When an external reference was applied, devices were functional as prior to the 200 krad(Si) irradiation. Therefore, with several new devices that have not been irradiated, the 200 krad(Si) irradiated devices were further irradiated to 1 Mrad(Si). No functional failure or significant parametric degradation was observed up to 1 Mrad(Si).

The reference output short circuit current along with the reference output voltage was measured to investigate the internal reference output buffer current drive capability degradation. The maximum data book specification reference voltage variation is 20 mV. Thus, according to Figure 6, devices should not

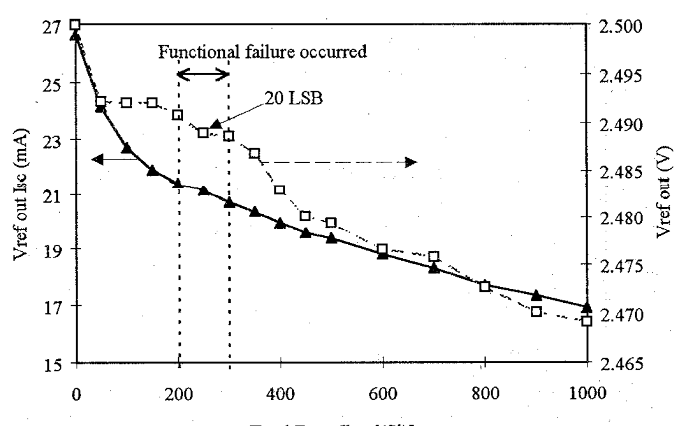

Figure 6. AD9871 reference output voltage and short circuit current degradation with HDR 50 rad(Si)/s. These measurements were taken with an external reference voltage applied to devices.

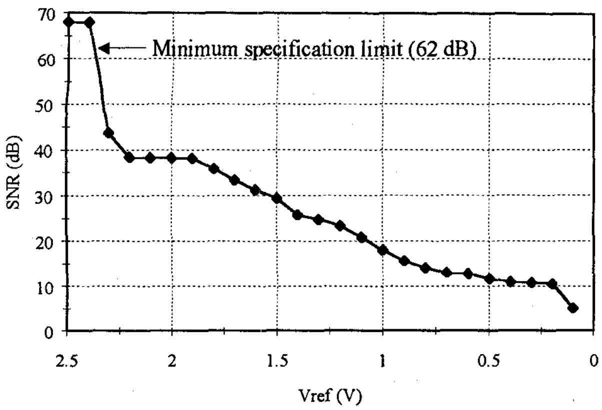

Figure 7. AD9871 signal-to-noise ratio vs. reference input voltage, input signal frequency of 1 MHz.

have been failed functionally at least above 400 krad(Si) because the corresponding degraded reference voltage is about 2.480 V. However, the reference output short circuit current degraded severely, which indicated that the drive current of the reference output buffer amplifier degraded significantly so that there is not enough current to drive the reference input of the converter with the reference output buffer amplifier. These parameters were measured with an external voltage reference was applied to devices so that devices were fully functional with a proper load.

The performance of AD9871 was optimized for the 2.5 V reference input. The dynamic performance will degrade for any other reference voltage or degrade with any change in reference voltage. Figure 7 illustrates the signal-to-noise ratio (SNR) performance vs. reference voltage for a 1 MHz input sinewave. Note that if the reference voltage is degraded during a conversion, conversions in the pipeline of internal circuits will be invalidated and cause functional failures. This also represents the importance of the reference voltage for functionality of the converter.

A low dose rate test at 0.005 rad(Si)/s is still in progress. However, at 85 krad(Si), the current low dose-rate level, no significant degradation was observed for this rad-hard 12-bit converter.

C. DATEL ADS937 Hybrid 16-bit ADC

This hybrid converter has error-correction circuitry but failed catastrophically after 25 krad(Si) with HDR. Due to the limited availability of test samples and constrained time-schedule for a project, devices were divided into different groups to be irradiated with a HDR to different radiation levels and sent to DATEL for post electrical measurements. This is not an usual procedure for total dose radiation test. However, it was done to satisfy a particular project requirement. No LDR test was conducted for this device.

SNR degraded significantly and decreased to the minimum specification limit at below 5 krad(Si) as shown in Figure 8. Devices irradiated to beyond 25 krad(Si) failed catastrophically. SNR of devices irradiated to 25 krad(Si) showed the SNR degraded to 50 dB. This SNR degradation will make theoretically this 16-bit converter to only an 8-bit effective converter at 25 krad(Si). This is a significant degradation for any precision system applications. SNR and other parameters of devices irradiated to 50 krad(Si) could not be measured due to catastrophic functional failure of converter. Devices did not recover during annealing test for both radiation level devices.

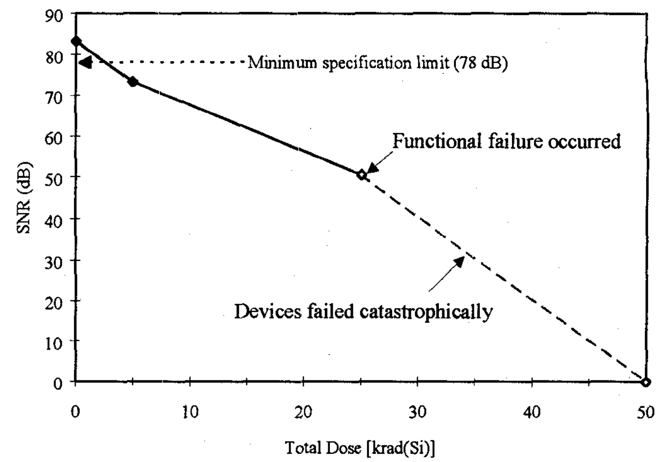

Figure 8. DATEL ADS937 hybrid converter SNR degradation with HDR 50 rad(Si)/s.

Supply current of converter did not show much degradation at 25 krad(Si). This is a quite different result to a CMOS monolithic converter which showed a large increase in supply current at below 10 krad(Si) and recovered after room temperature annealing [4].

The ADS937 device contains two internal flash A/D converter and digital error-correction logic circuitry. An external 5 V reference voltage is required for operation. The technologies of these critical components are not available at this time. However, they are probably similar technologies to those converters studied in this paper. This hybrid converter which contains bipolar, CMOS, and BiCMOS components in one package is very sensitive to total dose irradiation and showed severe degradation at very low total dose levels. This is consistent with a CMOS monolithic 16-bit converter that was previously tested and it is discussed in the following section.

D. Crystal Semi. CS5016 CMOS 16-bit ADC

Similar results as DATEL ADS937 converter were observed for this CMOS 16-bit converter. The converter failed catastrophically at 4 krad(Si) with a high dose rate of 50 rad(Si)/s and devices recovered after room temperature annealing [4]. These results indicated that this CMOS converter was extremely sensitive to total dose irradiation.

At a low dose rate of 0.005 rad(Si)/s, INL exceeded the specification limit at 25 krad(Si) and other parameters showed small degradation until the final total dose level of 40 krad(Si). Power supply current is an effective parameter of global degradation of field oxide leakage or the subthreshold leakage of internal CMOS transistors. However, the power supply current did not show any degradation with LDR.

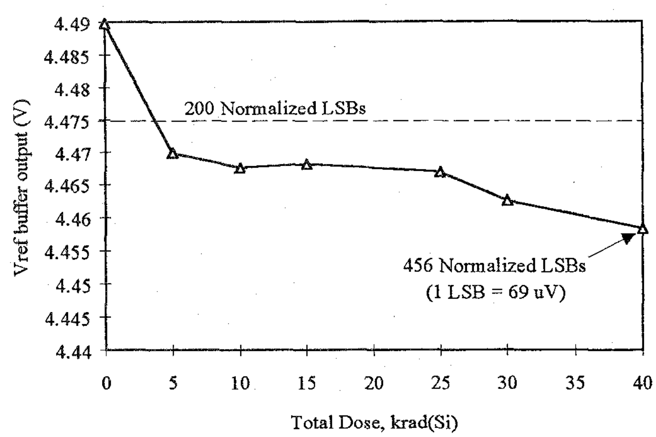

Figure 9. CS5016 reference buffer output voltage degradation at 0.005 rad(Si)/s.

This converter requires a 4.5 V external voltage for conversion of 16-bits and goes through an internal CMOS buffer amplifier. The output voltage of the buffer amplifier showed significant degradation at about 2 krad(Si) with LDR, a very low total dose level. The normalized LSB was calculated for the buffer amplifier voltage degradation and it is shown in Figure 9. One can expect that large degradation after 5 krad(Si) with dynamic parameters, such as SNR, because the severe degradation in reference voltage is directly related to the performance of the converter. However, SNR decreased about 7 dB at 40 krad(Si) and exceeded the minimum specification limit after 35 krad(Si). This is a small degradation in SNR compared to the reference buffer output voltage degradation. This is an interesting result and it is quite different than the result of the AD9871 converter, which its SNR was very sensitive to the reference voltage degradation (see Figure 7). This CMOS 16-bit converter perhaps can tolerate large changes in the reference buffer output voltage because of the internal error-correcting circuitry along with a *microprocessor-controlled* operation. This is a unique feature of this device. Sampling, calibration, and conversion can be placed under the microprocessor control. This is probably why the CS5016 converter performed much better at LDR and parametric shifts in the internal circuits were much less with LDR.

IV. Discussion

Reducing power consumption is far more difficult in analog circuit design than for digital circuits because of inherent limitations in bandwidth, resolution, and signal-to-noise ratio [9]. Some flash ADCs are designed and fabricated for low-power applications, but these converters do not have resolutions as needed in space applications. The most critical component in high accuracy SAR converters is the internal comparator which requires extremely close matching of parameters in analog circuitry. This is much easier to achieve in bipolar technology because of the inherently better matching and high transconductance of bipolar devices compared to CMOS devices.

Three different technologies are available for this particular 12-bit SAR type A/D converter. The older bipolar technology converter dissipates considerably more power. Therefore, it is not even comparable in power consumption to other two later technology converters. The CMOS converter is designed for low-power applications. However, the power dissipation increases as the radiation level increases and one of the key parameter, INL, also degraded significantly. The BiCMOS converter, on the other hand, can operate at much higher radiation levels than the CMOS converter with slight parametric degradation. Functional failure for the ADC574A BiCMOS converter occurred at much higher levels and was far higher than that of the previously tested Maxim MX674A BiCMOS converter [3]. The ADS574 CMOS converter failed abruptly at lower radiation levels with even LDR because of inherent limitations in CMOS technology.

The AD574 converter was the first 12-bit integrated circuit A/D converter. The device had two chips (bipolar and CMOS) in one ceramic package. A wide range of 574s device fabrication is currently available in bipolar, CMOS, and BiCMOS technologies. Their features vary slightly for different purpose circuit applications. The generic 574 converters have a limitation in conversion speed because of the successive-approximation-register (SAR) architecture. However, it is still the most popular converter in military and space applications. Thus, there is still a need for the device's radiation hardness from various manufacturers.

CMOS converters that anneal quickly may perform better in a LDR environment than BiCMOS converters. If a BiCMOS converter shows ELDR effect in bipolar components internal to the converter, the CMOS converter which perform better with LDR may be more suitable to use in space applications. However, LDR test results were quite different for two different Burr-Brown converters as shown in Figure 4. The CMOS converter showed even more degradation at LDR compared to the HDR results. The BiCMOS converter also showed slightly larger degradation with LDR than with HDR. This is an important test result because these CMOS COTS devices will show much more inconsistency in their test results with total dose irradiation. These CMOS devices observed abrupt failure because of inherent limitations in commercial CMOS technology and a critical parameter, INL, degraded much more at LDR. This is a significant result because one can underestimate the failure level of these CMOS devices at LDR environments. Furthermore, it suggests a LDR evaluation test for these CMOS devices even though they showed a classical annealing after HDR irradiation.

Analog Devices AD9871 rad-hard BiCMOS 12-bit converter showed a promising result for deep space missions. It was functional up to the final total dose level of 1 Mrad(Si) with an external reference. A precision external reference voltage must be used for applications greater than 200 krad(Si) to maintain converter accuracy. This is a somewhat opposite result compared to the BiCMOS AD7872 14-bit converter from the same manufacturer in terms of the usage of internal and external components to improve the total dose failure level. AD7872 is a commercially fabricated BiCMOS process converter and the converter functionally failed at 40 krad(Si) with an internal clock. However, it failed functionally at 4 krad(Si) using an external clock [4]. The external clock is connected to an internal CMOS amplifier and CMOS analog switches to bypass the internal clock. The sensitivity of these CMOS components determined the large differences in the converter radiation hardness with internal and external circuit application modes.

A careful part selection must be considered to provide an external reference voltage to the rad-hard AD9871 converter to be operational up to 1 Mrad(Si). A latest study of precision references in space applications showed that some COTS precision reference devices degraded severely at 20 krad(Si) [10]. This could limit the usage of the AD9871 converter after 200 krad(Si) where the internal reference failed. Note that parametric and functional measurements for the AD9871 converter were made with an external reference which was not subjected to total dose irradiation.

SNR of the ADS937 hybrid 16-bit converter failed below 5 krad(Si) with HDR and similar results were observed for the CS5016 monolithic CMOS technology 16-bit converter. Both converters have error-correcting circuitry to compensate some internal parametric changes. However, these converters failed functionally at very low total dose levels with HDR. This explains that even with self-calibrating and error-correcting circuits, devices can not achieve specified performance with severe parametric degradation caused by HDR total dose irradiation.

The previous test results on CS5016 CMOS 16-bit converter indicated that a better performance at LDR on this device because this converter has microprocessor-controlled error-correction and self calibration circuitry. In fact, devices showed good annealing behaviors after HDR irradiation. Devices recovered both functionally and parametrically at both room-temperature and subsequent high-temperature annealing [4]. Devices did not show any rebound effects during annealing test. This is another major reason for the better performance of this CMOS converter at low dose-rate environment. This device may be acceptable for use in some space applications.

V. Conclusions

Results from two different technology 12-bit converters, CMOS and BiCMOS, 574s from Burr-Brown showed that the BiCMOS devices performed better in total dose environment. LDR test results indicated that BiCMOS is still a better device technology than CMOS for space applications. The AD9871 radiation hardened converter showed a promising result and was functional up to 1 Mrad(Si) using a precision external reference to maintain converter accuracy. The ADS937 hybrid 16-bit converter failed at a low total dose level of 5 krad(Si) of HDR and similar results were observed for the CS5016 monolithic CMOS 16-bit converter. The CS5016 performed much better with LDR as expected for a CMOS device with classical annealing characteristics. However, the Burr-Brown ADS574 CMOS converter showed more degradation at LDR. This is an important result for low-power COTS CMOS devices because it implies a LDR test requirement for an evaluation.

There is a need for CMOS converters to overcome some of the basic limitations in total dose radiation responses and be able to use in high-speed, low-power, and small-size system applications. The BiCMOS technology, however, is able to provide high data-conversion speed utilizing the performance of npn transistors in the circuit which gives sufficient data conversion rate and bandwidth of the device. The power dissipation of BiCMOS devices would be typically slightly higher than CMOS devices, but it would be suitable for most digital data or imaging processing applications.

Finally, the BiCMOS technology appears to be the best technology choice of A/D converters for space applications. However, selective CMOS converters that perform much better at LDR should also be considered for use in low-power applications. This requires LDR testing for even commercial low-power CMOS converters to be used in space environments.

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